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Dr. Herschel Pilloff
Office of Naval Research
Physics Division (Code 1112LO)
800 North Quincy Street
Arlington, Virginia 22217-5000

Dear Hersch,

This is the final technical report of work accomplished under ONR Contract No. N00014-88-K-0042 (R&T 4124112) during the period 1987 December 1 to 1990 November 30. The body of the letter summarizes work accomplished under this contract; three appendices list publications, persons associated with the contract, and attendance and lectures at conferences and workshops. In the body names of persons associated with the contract are in italics. Publications are referred to by their number in appendix A.

• *Caves* explored application of squeezed light to laser stabilization. His emphasis shifted from earlier work on stabilizing intensity to stabilizing frequency (or phase) to a mode of an optical cavity. He investigated the use of squeezed light in the fringe-side scheme for frequency stabilization and in the widely used scheme in which one detects phase-modulated light on reflection from a cavity. This work was reported at the NATO Advanced Research Workshop on Squeezed and Non-Classical Light, held in Cortina, Italy, in 1988 January, and appeared in the proceedings of the Workshop [8].

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• Samuel *Braunstein* and *Caves* investigated the use of "chained" Bell inequalities to test the objectivity of quantum mechanics. They showed that chaining the standard (and tested) Clauser-Horne-Shimony-Holt Bell inequality can lead to inequalities that display stronger violations by quantum mechanics. They quantified the meaning of "stronger violations" by giving the strength of the violation in units of noise in a model experiment where the dominant noise is statistical. This work was reported at the International Symposium on Spacetime Symmetries at the University of Maryland in 1988 May and appeared in the proceedings of the Symposium [9]; it was reported again at the Bell's Theorem Workshop held at George Mason University in 1988 October and appeared in the proceedings of the Workshop [10]; and it was reported still again at the Third International Symposium on the Foundations of Quantum Mechanics in Tokyo in 1989 August and appeared in the proceedings of the Symposium [12]. The most extensive account of this work was published in *Annals of Physics* [1].

• Peter Drummond of the University of Queensland and *Caves* investigated the channel capacity of a wideband communications channel that has a constraint on its mean power P. They found a capacity given approximately by $\sqrt{P/h}$ bits/sec, both for direct detection of number states and for heterodyne detection of squeezed states, and they suggested that a high T_c superconducting waveguide might meet the physical requirements for attaining the limiting capacity. This work was written up as a very short paper and submitted, first to *Nature* and then to *Physical Review A*, but it did not fare well with referees who believe that the $\sqrt{P/h}$ limit can be surpassed. During the past year Drummond and Caves constructed a nearly airtight proof of the $\sqrt{P/h}$ limit, and they identified flaws in all the previous work that purported to find an infinite wideband capacity. These results, plus additional work on the information flux of a multi-mode bosonic channel, have been written up in a much longer paper [6], which has been distributed for comments and which the authors hope to submit to *Physical Review A* by February 1.

• Bonny *Schumaker* continued work on ultrasqueezed light produced by multi-frequency pumping of three-wave and four-wave interactions. For both the three-wave and four-wave cases she has quantified the ultimate noise reduction that can be achieved by use of an optimal detection scheme, and she has shown in both cases that for a fixed pump power one can achieve a greater noise reduction by dividing the power among several pump frequencies, thus producing ultrasqueezed light. The PI has been assured repeatedly that this work is being written up in two papers, one theoretical and one experimental (co-authored with R. M. Shelby of IBM San Jose), but there is presently no sign of their being completed.

- Chang *Zhu* and *Caves* calculated the photocount statistics of cw squeezed light that has a flat squeezing spectrum and a monochromatic mean field. They found that a combination of multiple modes and inefficiencies washes out the Schleich-Wheeler oscillations associated with a single-mode squeezed state that has a mean coherent excitation, but that the oscillations associated with a single-mode squeezed vacuum survive into the cw distribution under appropriate conditions. *Zhu* reported these results at the Rochester Conference in 1989 June [11], and *Caves* described them at the 1989 Annual Meeting of the Optical Society of America in 1989 October [17]. A more extensive account has been published in *Physical Review A* [2].

- *Braunstein*, Gerard Milburn of the University of Queensland, and *Caves* developed a measurement model, involving four detectors, for a particular "canonical" form of the positive P representation, a widely used phase-space distribution in quantum optics. Their work begins the process of interpreting the positive P representation, and their model shows why the positive P representation produces normally ordered moments. A publication describing these results is scheduled for publication in *Physical Review A* [3].

- *Zhu*, *Caves*, Milburn, and Wolfgang Schleich of the Max Planck Institute for Quantum Optics calculated the photon statistics of ideal two-mode squeezed light. The joint photon-number probability for the two modes displays structure similar to the Schleich-Wheeler oscillations for ideal single-mode squeezed light. As for the single-mode case, the structure can be explained in terms of interference in phase space, except that now the phase space is four dimensional. An account of this work is scheduled for publication in *Physical Review A* [4].

- *Braunstein* and *Caves* considered a nonpolarization Bell inequality experiment, which was proposed by Franson and by Horne, Shimony, and Zeilinger and which was carried out recently by Rarity and Tapster. In a Comment submitted to *Physical Review Letters* [5], *Braunstein* and *Caves* identified the properties whose local objective status is checked by the Rarity-Tapster experiment and suggested that a Bell inequality for these quantities is less than compelling. The Comment has been accepted and awaits adjudication of the Replies before publication.

- *Lane*, *Braunstein*, and *Caves* initiated work on the Shapiro-Shepard-Wong (MIT) proposal for high-sensitivity phase measurements. They showed that the MIT proposal cannot lead to high sensitivity in a single measurement, and they went on to analyze the performance of the MIT proposal in a sequence of measurements. Extensive computer simulations showed that even in a sequence of measurements, the MIT proposal does no better than squeezed-state interferometry and suffers from serious practical problems besides. A preliminary version of these results was reported at the 1990 Annual Meeting of

the Optical Society of America (publication 18), and an exhaustive account is now being prepared for publication.

Sincerely,

Carlton M. Caves

CMC/TeX

APPENDIX A: PUBLICATIONS

Contract No. N00014-88-K-0042 (1987 December 1 to 1990 November 30)

1. Technical articles in refereed journals

1. S. L. Braunstein and C. M. Caves, "Wringing out better Bell inequalities," *Annals of Physics* **202**, 22–56 (1990).

2. C. Zhu and C. M. Caves, "Photocount distributions for continuous-wave squeezed light," *Physical Review A* **42**, 6794–6804 (1990).

3. S. L. Braunstein, C. M. Caves, and G. J. Milburn, "Interpretation for a positive *P* representation," *Physical Review A*, to be published.

4. C. M. Caves, C. Zhu, G. J. Milburn, and W. Schleich, "Photon statistics of two-mode squeezed states and interference in four-dimensional phase space," *Physical Review A*, to be published.

5. S. L. Braunstein and C. M. Caves, "Nonpolarization Bell inequalities for photons," *Physical Review Letters*, to be published.

6. P. D. Drummond and C. M. Caves, "Quantum limits on wideband communication rates," extensively revised for re-submission to *Physical Review A*.

2. Other technical articles

7. D. D. Crouch, "Squeezed states of the electromagnetic field," Sec. 17.9 of A. Yariv, *Quantum Electronics*, Third Edition (Wiley, New York, 1988).

8. C. M. Caves, "Laser stabilization using squeezed light," in *Squeezed and Nonclassical Light*, edited by P. Tombesi and E. R. Pike (Plenum, New York, 1989), pages 29–38.

9. S. L. Braunstein and C. M. Caves, "Wringing out better Bell inequalities," in *Proceedings of the International Symposium on Spacetime Symmetries*, edited by Y. S. Kim and W. W. Zachary, *Nuclear Physics B (Proceedings Supplements Section)* **6**, 211–221 (1989).

10. S. L. Braunstein and C. M. Caves, "Chained Bell inequalities," in *Bell's Theorem, Quantum Theory and Conceptions of the Universe*, edited by M. Kafatos (Kluwer, Dordrecht, 1989), pages 27–36.

11. C. Zhu and C. M. Caves, "Photostatistics of continuous-wave squeezed light," in *Coherence and Quantum Optics VI*, edited by J. H. Eberly, L. Mandel, and E. Wolf (Plenum, New York, 1989), pages 1279–1283.

12. S. L. Braunstein and C. M. Caves, "Wringing out better Bell inequalities," in *Foundations of Quantum Mechanics*, edited by S. Kobayashi, H. Ezawa, Y. Murayama, and S. Nomura (Physical Society of Japan, Tokyo, 1990), pages 161–170.

3. Abstracts of papers presented at meetings

13. C. M. Caves, "Quantum precision measurement: An overview," *Bulletin of the American Physical Society* **33**, 725 (1988).

14. C. M. Caves, "Squeezed light: Darker than dark," *Proceedings of 1988 LEOS Annual Meeting*, Santa Clara, California, 1988 November 2–4 (IEEE, Piscataway, New Jersey, 1988), pages 106–109.

15. C. M. Caves, "Precision measurements using nonclassical effects," *Conference on Quantum Electronics and Laser Science, 1989 Technical Digest Series*, Vol. 12 (Optical Society of America, Washington, D.C., 1989), pages ?10–212.

16. C. M. Caves, "Nonclassical states of light," *1989 OSA Annual Meeting, 1989 Technical Digest Series*, Vol. 18 (Optical Society of America, Washington, D.C., 1989), page 115.

17. C. Zhu and C. M. Caves, "Photocount statistics of continuous wave squeezed light," *1989 OSA Annual Meeting, 1989 Technical Digest Series*, Vol. 18 (Optical Society of America, Washingtou, D.C., 1989), page 147.

18. S. L. Braunstein, C. M. Caves, and A. S. Lane "Maximum-likelihood statistics of multiple quantum phase measurements," *OSA Annual Meeting, 1990 Technical Digest Series*, Vol. 15 (Optical Society of America, Washington, D.C., 1990), page 114.

APPENDIX B: PERSONNEL

Contract No. N00014-88-K-0042 (1987 December 1 to 1990 November 30)

- *Carlton M. Caves.* Associate Professor of Electrical Engineering and Physics and principal investigator. Partial salary support.

- *Alistair S. Lane.* Postdoctoral Research Scientist at USC beginning 1989 January 1. Partial salary support.

- *Bonny L. Schumaker.* Part-time Research Scientist at USC. Partial salary support during the period 1988 March 1 to 1989 February 28.

- *Samuel L. Braunstein.* Graduate student at Caltech (received Ph.D. in Physics in 1988 June) and occasional visitor to USC. No salary support.

- *David D. Crouch.* Graduate student at Caltech (received Ph.D. in Applied Physics in 1988 June). No salary support.

- *Chang Zhu.* Graduate student at USC. Partial support as a Graduate Research Assistant.

- *Shang Song.* Graduate student at USC. Partial support as a Graduate Research Assistant.

APPENDIX C: CONFERENCES AND WORKSHOPS

Contract No. N00014-88-K-0042 (1987 December 1 to 1990 November 30)

- NATO Advanced Research Workshop on Squeezed and Non-Classical Light, Cortina, Italy, 1988 January 25–29. Invited speaker: *Caves*.
- Symposium on Precision Measurement and Squeezed Light, American Physical Society General Meeting, New Orleans, 1988 March 21–25. Invited speaker: *Caves*.
- International Symposium on Spacetime Symmetries, University of Maryland, 1988 May 24–28. Invited speaker: *Caves*; attended: *Braunstein*.
- Bell's Theorem Workshop, George Mason University, 1988 October 21–22. Invited speaker: *Braunstein*.
- IEEE/LEOS Annual Meeting, Santa Clara, California, 1988 November 2–4. Invited speaker: *Caves*.
- Snowbird Conference, Snowbird, Utah, 1989 January 11-12. Invited speaker: *Caves*.
- Conference on Quantum Electronics and Laser Science, Baltimore, 1989 April 24–28. Invited speaker: *Caves*.
- Sixth Rochester Conference on Coherence and Quantum Optics, Rochester, 1989 June 26–28. Attended: *Caves, Lane, Song, Zhu*.
- Third International Symposium on the Foundations of Quantum Mechanics, Tokyo, 1989 August 28–31. Invited speaker: *Caves*.
- Annual Meeting, Optical Society of America, Orlando, 1989 October 15–20. Tutorial lecturer: *Caves*.
- International Quantum Electronics Conference, Anaheim, 1990 May 21–25. Attended: *Caves, Lane, Zhu*.
- Annual Meeting, Optical Society of America, Boston, 1990 November 4–9. Attended: *Caves*.